Nuclear Reaction Experiments

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The current status and future of transactinide heavy element production

Yu.Ts. Oganessian[1]

[1] Joint Institute for Nuclear Research, Russia

oganessian@flnr.jinr.ru

[Abstract not available at time of printing]

Reaction studies and the synthesis of superheavy elements at GSI

D. Ackermann[1,2]

[1] Johannes Gutenberg Universität Mainz, Germany
[2] GSI, Germany

d.ackermann@gsi.de

Introduction

The search for superheavy elements, predicted close to the double magic nucleus ^{298}114 [1] was a substantial motivation for the construction of the UNILAC and the velocity filter SHIP [2] at GSI in Darmstadt. Following the concept of "cold" fusion of lead or bismuth targets with medium heavy projectiles like ^{40}Ar or ^{50}Ti, first applied successfully by Oganessian et al [3], the SHIP group succeeded to produce and identify about 25 new isotopes with atomic numbers from Z=98 up to Z=112. Mutual interaction of experimental results and theoretical calculations led to a better understanding of their stability, while measured excitation functions allowed for a reliable empirical extrapolation of optimum bombarding energies and cross sections for 1n de-excitation channels. Continuous technical development pushed the sensitivity of the set-up down to a cross section value of about 1 pb. To proceed towards higher Z an extensive development program is being followed at present. Recently the synthesis of isotopes of the elements 114 and 116 has been reported at Dubna. The unambiguous assignment of those events, however, is not yet possible. A recent review on the discovery of the heaviest elements [4] gives a complete overview over the recent achievements in the field. There can also be found a detailed description of the experimental set-up at GSI.

Recent results on the synthesis of heavy elements with Z=110-112

The elements with Z=107-112 have been synthesized and unambiguously identified at SHIP. The elements 107-109 have already been named and have been entered as Bohrium (Bh, Z=107), Hassium (Hs, Z=108) and Meitnerium (Mt, Z=109) in the periodic table of elements. The properties found for the elements 110, 111 and 112 are presented in this section. In an experiment in November 1994 four α-decay chains were observed, which were attributed to the isotope with the mass number 269 of the new element 110 [5]. The production cross section was $\sigma=3.5(^{+2.7}_{-1.8})$pb. In a directly following experiment in November/December 1994 the ER production by the reaction ^{64}Ni + ^{208}Pb was investigated at E^*=(8-13)MeV. Nine α-decay chains observed in this experiment could be attributed to ^{271}110. A maximum cross section of $\sigma=15(^{+9}_{-6})$pb was measured at E^*=12.1MeV. In an experiment in October 2000 we observed in the reaction ^{64}Ni + ^{207}Pb eight decay chains of correlated ER-α-fission events which we attribute to the decay of the new isotope ^{270}110. Also the daughter and grand daughter products ^{266}Hs and ^{262}Sg have not been observed before [6]. On the basis of these encouraging results for the synthesis of element 110 in the reactions ^{62,64}Ni + ^{208}Pb the production of an isotope of element 111 by the reaction ^{64}Ni + ^{209}Bi was undertaken in December 1994. A total of three decay chains attributed to ^{272}111 was observed with a maximum cross section of $\sigma=3.5(^{+4.6}_{-2.3})$pb [7]. In the series of experiments performed in October 2000 we also confirmed the synthesis of ^{272}111 observing additional three decay chains of this isotope. In early 1996 using the projectile target combination ^{70}Zn + ^{208}Pb two decay chains which had been attributed to ^{277}112 were reported [7]. It was found later that one of the decay chains was spuriously generated [8]. In a recent

experiment in May 2000 a second decay chain of ^{277}112 was recorded. It is shown together with the first chain from 1996 in Figure 1.

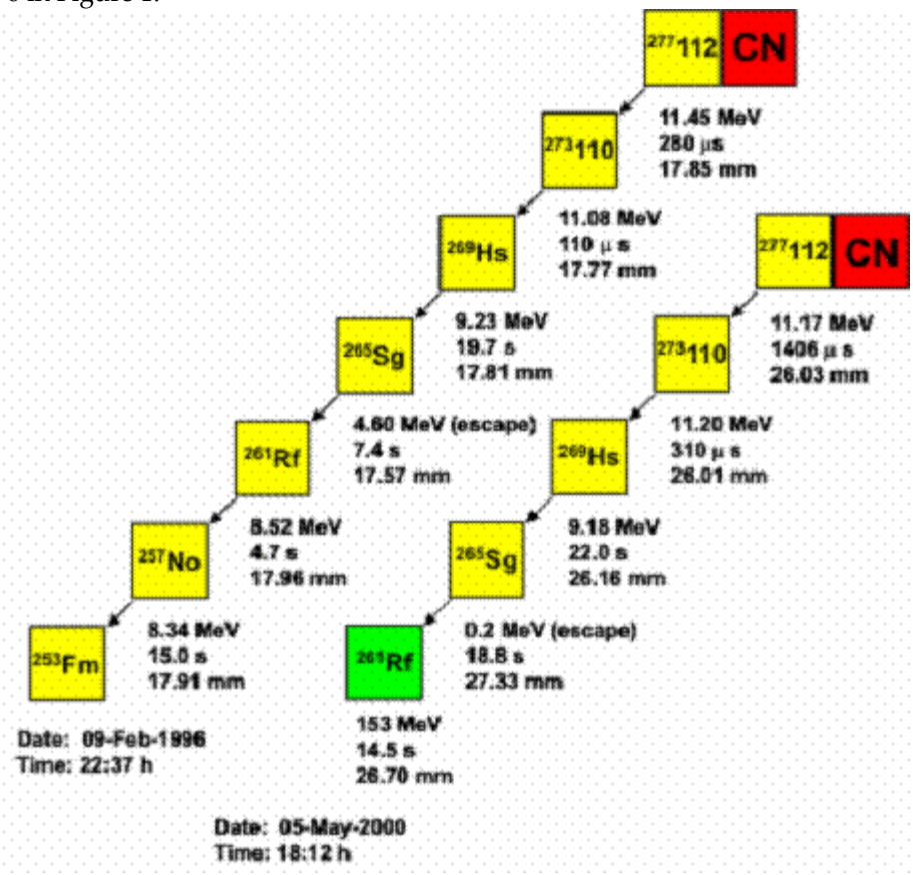

Figure 1. The two decay chains observed for ^{277}112 in 1996 and 2000.

For this isotope a maximum cross section of $\sigma=0.5(^{+1.1}_{-0.4})$pb has been observed [8]. The chain observed in the second measurement ends with the fission of ^{261}Rf in difference to the first chain which ran all the way down to. Both decay modes of ^{261}Rf have been observed also in an experiment on the chemistry of Hs where this isotope was produced in the decay chain of ^{269}Hs [9] confirming our findings.

Reaction mechanism studies

The steep decrease with increasing Z of production cross section observed for reactions with Pb and Bi-targets and for previous reactions on actinide targets has been contrasted by recent observations made in Dubna. There decay chains have been seen in bombardments of ^{244}Pu and ^{248}Cm with ^{48}Ca projectiles, which were interpreted as the decay of ^{288}114 [10] and ^{292}116 [11] with a more less constant production cross section of about 1pb. According to recent self-consistent calculations [12] these nuclei are close to the region where a stabilisation due to shell effects can be expected. However, it was up to now not possible to detect an increasing production cross section for heavy ER's with magic proton or neutron numbers [13,14,15]. For medium to heavy masses it has been shown that nuclear structure and nuclear deformation are important ingredients for the formation of the compound system [16,17]. We have started a program to examine the reaction mechanism in the vicinity of the closed proton shell at Z=82 and N=126 using the partial wave (spin) distribution σ_ℓ [18]. It has been shown that one can extract from the spin distribution information on the barrier structure for heavy ion collisions [19]. Moreover, it yields

information on the single partial wave cross sections and can reveal effects at high angular momentum, which might hint at a stabilisation due to shell effects as shown schematically in Figure 2.

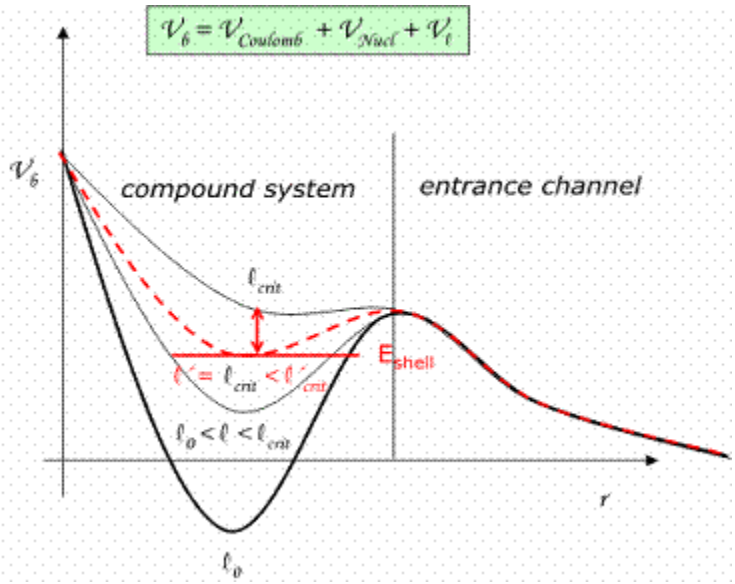

Figure 2. Cartoon illustrating the effect of a shell correction energy E_{shell} on the critical angular momentum for fusion l_{crit}.

Technical development at SHIP

The three areas presently under technical investigation at SHIP are beam development, target development and background reduction. To access a region of lower cross section the number of interactions and, therefore, the number of projectiles has to be increased. The UNILAC at GSI delivers the beam with a duty cycle of about 28%. Apart from raising the beam current, the use of an accelerator with 100% duty cycle (DC) would already provide a factor of 3.5 in higher beam intensity. The ongoing progress in the development of high frequency (28GHz) ECR ion sources promises an increase in beam intensity of another factor of 2-10. The increased beam current, together with a higher Z of the projectiles in some cases, asks for measures to protect the Pb and Bi targets, both having a low melting point. A first step is to spread the beam as homogeneous as possible over a maximum area. With the target wheel presently in use we have already reached the limit for the presently available beam intensities. The introduction of ion optical elements like octupole magnets in the UNILAC beam-line will help to approach the desired optimum of a rectangular beam profile, illuminating the target as uniformly as possible. Besides those "passive" measures also an "active" target cooling is now under development. A set-up providing a gas jet blown onto the spot where the beam hits the target is currently being developed. Chemical compounds of Pb or Bi with higher melting temperatures are also under investigation. We have obtained first promising results with PbS foils sandwiched between two thin layers of carbon. The higher projectile rate required for a successful investigation of reactions with lower cross section will have as a consequence an increase of background per time unit. To improve the background suppression we test the use of foils to stop scattered beam particles which pass SHIP with low kinetic energy. The high energy particles can be suppressed more effectively by in increased deflection in the last magnetic dipole of SHIP.

Acknowledgments

The recent experiments were performed together with H.-G. Burkhard, F.P. Heßberger, S. Hofmann, B. Kindler, G. Münzenberg, B. Lommel, H.-J. Schött, P. Kuusiniemi (GSI Darmstadt), A.G. Popeko, A.V. Yeremin (FLNR-JINR Dubna), S. Antalic, P. Cagarda, R. Janik, Š. Šaro (University of Bratislava), J. Uusitalo and M. Leino (University of Jyväskylä).

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Status and future of transactinide reaction experiments at RIKEN

K. Morita[1]

[1] Cyclotron Center, RIKEN, Japan

morita@rarfaxp.riken.go.jp

[Abstract not available at time of printing]

Sub-barrier fusion in the ^{48}Ca + ^{208}Pb reaction

W.D. Loveland[1], J.B. Patin[2], D. Peterson[1], K.E. Gregorich[2], N. Myers[1], P. Miranda[1], T.N. Ginter[2], K. Aleklett[3]

[1] Oregon State University, USA
[2] Lawrence Berkeley National Laboratory, USA
[3] Uppsala University, Sweden

lovelanw@ucs.orst.edu

The study of the heaviest elements offers one an opportunity to study nuclear structure and nuclear dynamics under the influence of large Coulomb forces. Many years ago, Oganessian recognized the special importance of the doubly magic ^{208}Pb in the synthesis of the heaviest elements [1]. He showed the low excitation energies of the compound nuclei in reactions with ^{208}Pb or ^{209}Bi targets (so-called "cold fusion") (Figure 1) could be utilized to produce heavy nuclei via reactions like $^{208}Pb(X,n)$ or $^{209}Bi(X,n)$.

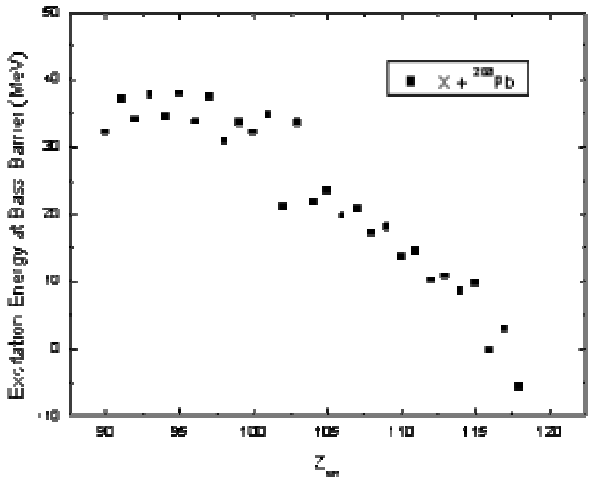

Figure 1. Excitation energies at the Bass barrier for reactions with ^{208}Pb targets.

Using this cold fusion approach, elements 107-112 were successfully synthesized at GSI [2]. The cross sections for these reactions decreased sharply with increasing Z. Attempts to produce element 113 using the cold fusion reaction $^{209}Bi(^{70}Zn,n)$ were not successful [2] with an upper limit cross section of 0.6 pb. Attempts to produce element 118 using the $^{208}Pb(^{86}Kr,n)$ reaction were also unsuccessful [3] with an upper limit cross section of ~ 0.2 pb. These findings have generally been taken to indicate the need for significant technical advances before further element synthesis with cold fusion reactions is feasible.

The reaction of the two doubly magic nuclei, ^{48}Ca and ^{208}Pb is one of the most interesting and experimentally challenging cold fusion reactions. The optimal excitation energy for a "1n" reaction is about 13 MeV. As seen in Figure 1, this requires a reaction that occurs significantly below the fusion barrier for the ^{48}Ca + ^{208}Pb system. We report an experimental study of the cold fusion reaction $^{208}Pb(^{48}Ca,n)$ and a search for the occurrence of the radiative capture reaction $^{208}Pb(^{48}Ca,\gamma)$. This study was

undertaken to better understand the capture and fusion probabilities in cold fusion reactions involving n-rich projectiles that might be of interest in the synthesis of heavy nuclei.

The reaction of ^{48}Ca with ^{208}Pb has been extensively studied [4-17,27] , especially the ^{208}Pb(^{48}Ca,2n) reaction. Some of these experimental studies have used this reaction to do nuclear spectroscopy of the transfermium nuclei [10,13-15] but most studies have dealt with measuring cross sections for this reaction. Extensive measurements also exist for the related reaction of ^{48}Ca with ^{206}Pb [18]. For the ^{208}Pb(^{48}Ca,n) reaction, cross sections of <27, 260 ± 30and 180 ± 53 nb have been reported for projectile energies of 208, 212, and 216 MeV, respectively.[7] To the best of our knowledge, no previous measurements of the radiative capture cross section have been made for this system

The reaction of ^{48}Ca with ^{208}Pb was studied at the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory, using the Berkeley Gas-filled Separator (BGS) [19]. The experimental apparatus was a modified, improved version of the apparatus used in [19], including improved detectors and data acquisition system, continuous monitoring of the separator gas purity, and better monitoring of the ^{48}Ca beam intensity and energy. A $^{48}Ca^{10+}$ beam was accelerated to various energies at typical beam currents of ~ 200 particle nanoamperes. The beam went through the 0.040 mg/cm^2 carbon entrance window of the separator and struck a ^{208}Pb target placed 0.5 cm downstream from the window. The targets were 460 mg/cm^2 thick (sandwiched between 35 mg/cm^2 C on the upstream side and <9 mg/cm^2 C on the downstream side). Nine of them were mounted on a wheel that rotated at 300 rpm. Beam energies at the center of the target were determined using the range-energy data of Hubert et al.[20] The beam intensity was monitored by two silicon detectors (mounted at ± 27° with respect to the incident beam) that detected elastically scattered beam particles from the target. Attenuating screens were installed in front of these detectors to reduce the number of particles reaching them (and any subsequent radiation damage to the detector.) The run lasted 60 hours.

The EVRs (E ~ 40 MeV) were separated spatially in flight from beam particles and transfer reaction products by their differing magnetic rigidities in the gas-filled separator. The separator was filled with helium gas at a pressure of 0.8 torr. For all the measurements, the magnetic field of the separator was set to 2.107 Tm, a setting that produced an optimum distribution of the EVRs on the focal plane detector for the ^{208}Pb(^{48}Ca, 2n)^{254}No reaction. (Using the semi-empirical relationships in [5] would give a predicted value of the optimum Br of 2.099 Tm). The efficiency of the separator for transport of recoils from the target to the focal plane detector was measured to be 57% for the reaction of 200 MeV ^{48}Ca with ^{176}Yb, assuming a cross section for this reaction of ~ 790 mb. (This latter value was extrapolated from the measured data of Sahm, et al. [21]). Monte Carlo simulations of the ion optics of the BGS [3] are consistent with this value (51%). We measured a transport efficiency of 45% for the reaction of 215 MeV ^{48}Ca + ^{208}Pb $\rightarrow$ ^{254}No + 2n. (This efficiency is based on a cross section for the ^{208}Pb^{48}Ca, 2n) reaction of 3.4 mb. [7] This value of the efficiency was used in all calculations.

In the focal place region of the separator, the EVRs passed through a 10 cm x 10 cm parallel plate avalanche counter (PPAC) [22] that recorded the time, DE, and x,y position of the particles. This PPAC has an approximate thickness equivalent to 0.6 mg/cm^2 of carbon. The time-of-flight of the EVRs between the PPAC and the focal plane detector was measured. The PPAC was used to distinguish (97.5 - 99.5% efficiency) between particles hitting the focal plane detector that were beam-related and events due to the decay of implanted atoms.

After passing through the PPAC, the recoils were implanted in a 32 strip, 300 mm thick passivated ion implanted silicon detector at the focal plane that had an active area of 116 mm x 58 mm. The strips were position sensitive in the vertical (58 mm) direction. The position resolution along each strip was measured to be 0.70 mm for recoil-a correlations in the ^{208}Pb(^{48}Ca,3n) reaction. The energy response of each strip of the focal plane detector was calibrated using implanted recoils. An average energy resolution of ~ 40 keV for 5-9 MeV a-particles was measured for this detector.

In searching for the cold radiative capture channel ^{208}Pb(^{48}Ca,γ), one must be cautious not to confuse the decay of 2.91s ^{256}No (E_α=8.448, 8.402 MeV) with the decay of 2.3 s ^{252}No (E_α=8.42, 8.37 MeV). (^{252}No can be produced by the ^{208}Pb(^{48}Ca,4n) reaction or by the ^{206}Pb(^{48}Ca,2n) reaction from any ^{206}Pb impurities in the ^{208}Pb target). These channels can be resolved by either looking at EVR-α-α correlations for the ^{252}No decay which leads to 36s ^{248}Fm (E_α=7.87,7.83 MeV) rather than the 25.4 hr ^{252}Fm (from the ^{256}No) or by looking for the more prevalent spontaneous fission branch of the ^{252}No (SF 26.9%) vs an SF branch of 0.53% for ^{256}No. In addition, the ^{208}Pb(^{48}Ca,4n) reaction is energetically forbidden for projectile energies less than 223 MeV.

In studying the product of the (^{48}Ca,n) reaction, ^{255}No, one must be careful to disentangle the decay of ^{255}No ($t_{1/2}$=3.1 min, E_α 7927, 8007, 8077, 8121 keV), ^{254}No ($t_{1/2}$=55s, E_α=8093 keV) and ^{253}No($t_{1/2}$=1.7 min, E_α=8010 keV). We used two approaches to this decay curve resolution. At the higher energies, we used the 7927 line to calculate the cross section after resolving its decay curve while at the lower energies, we resolved the complex decay curves.

For center of target projectile energies of 204, 206.5, 207.8, 209.1, and 211.6 MeV with associated particle doses of 2.50 x 10^{16}, 2.40 x 10^{16}, 1.90x10^{16}, 3.50x10^{16}, and 4.90x10^{16}ions, no events corresponding to the production of ^{256}No were observed. This corresponds to one-event upper limit cross sections of 134, 139, 176, 95 and 68 pb, respectively.

Heavy ion radiative capture has been observed previously [23] and was the basis for an unsuccessful attempt to synthesize element 116 using the ^{208}Pb(^{82}Se,γ) reaction [2]. Two mechanisms for a possible cold radiative capture reaction of the type ^{208}Pb(^{48}Ca,γ) are fusion of the projectile and target nuclei in which the giant dipole resonance (GDR) of the compound system is excited and decays by the emission of GDR photons or production of a completely fused system whose (E*,J) are within one neutron binding energy of the yrast line, leading to a γ-ray cascade down to the ground state without particle emission. The latter possibility for the ^{208}Pb + ^{48}Ca reaction seems less likely given the data of Reiter et al.[15]who showed the entry distributions in the (E*,J) plane for the ^{208}Pb(^{48}Ca,2n) reaction at a similar energy (~ 215 MeV) are sharply tilted relative to the yrast line, suggesting that the initial compound system states do not fulfill the condition of being within one neutron binding energy of the yrast line.

The giant dipole resonance in ^{256}No should be around E* ~ 12-13 MeV, according to the systematic rule that the resonance position is given by 79 $A^{-1/3}$ [24] with a width of 4-6 MeV, which is similar to the range of excitation energies studied (E*=12-18 MeV) (neglecting the splitting of the GDR in the deformed ^{256}No). Thus, from an energetic point of view, decay by GDR photons was possible.

We can make some crude estimates to see if the observed upper limits for the radiative capture reaction are reasonable. If we write for the radiative capture cross section, $\sigma_{x,\gamma}$

$$\sigma_{x,\gamma}=\sigma_C \cdot P_{CN} \cdot W_\gamma$$

where σ_C is the capture cross section, P_{CN} the probability of going from the capture configuration to the completely fused configuration and W_γ is the probability of de-excitation by emission of GDR photons, we can make some order of magnitude estimates for the quantities involved to see if the failure to observe radiative capture is reasonable. The capture cross sections have been measured to be ~ 5 mb for the energy range in question [9], W_γ has been estimated to be 5 x 10^{-5} [23] and thus to get the observed upper limit cross section of 100 pb, we would need P_{CN} to be < 4 x 10^{-3}. Use of the semi-empirical estimates of P_{CN} in ref [25] for this case would give P_{CN} to be ~ 2 x 10^{-3} in agreement with the observed upper limit. Thus, because the centroid of the GDR resonance was 5-10 MeV below the Bass barrier for the reaction in question, our ability to observe cold radiative capture was reduced.

In Figure 2, we show the measured excitation function for the ^{208}Pb(^{48}Ca,n)^{255}No reaction along with a previous measurement. At projectile energies of 211.6 and 215.2 MeV (E*=18.6 and 21.7 MeV) , we are unable to resolve the decays of ^{255}No and ^{254}No with the entire decay curve being consistent with being

due to ^{254}No. . The peak cross section for the 1n channel is ~100 nb at a projectile energy of 209.1 MeV (E*=16.1 MeV). The capture cross section at this projectile energy is ~9 mb [9]. If we write the evaporation residue production cross section, σ_{EVR}, as

$$\sigma_{EVR}=\sigma_C \cdot P_{CN} \cdot W_{SUR}$$

then the product of P_{CN} and W_{SUR} is 1.1 x 10^{-5}. This estimate is interesting because it is a low value. Two possible ways of looking at this are as follows. If we take the estimates [26] of W_{SUR} ($=\Gamma_n/\Gamma_{total}$)=10^{-2} for ^{256}No excited to 16.1 MeV, then P_{CN} is 10^{-3} which is an unexpectedly large fusion hindrance for this reaction where Z_1Z_2=1640. On the other hand, if we use the semi-empirical systematics of Armbruster [25] for P_{CN}, we would estimate P_{CN} for this reaction to be 6 x 10^{-3} and a value of W_{SUR}=1.9 x 10^{-3} would result. We are attempting to resolve this ambiguity.

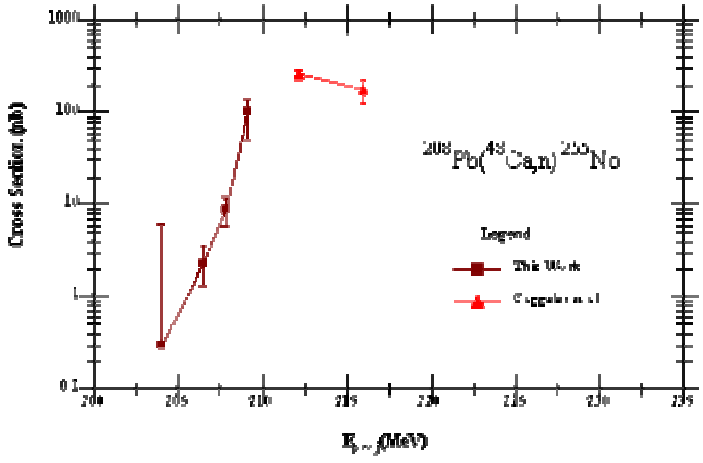

Figure 2. Measured cross sections for the ^{208}Pb(^{48}Ca,n) reaction.

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Production and study of super-heavy nuclei at GANIL

J. Péter[1], A. Drouart[2], C. Stodel[3]

[1] FULIS, Laboratoire de Physique Corpusculaire, France
[2] FULIS, SPhN - DAPNIA, France
[3] FULIS, GANIL, France

jpeter@in2p3.fr

In recent years, experiments on the production of super-heavy nuclei have been undertaken at Ganil, taking advantage of the powerful velocity filter LISE3 and the high intensity ECR ion sources. Some modifications were made to the velocity filter: - slits, a beam profiler and a Faraday cup were installed between its two identical halves –higher voltage power supplies were installed in order to accommodate experiments in reverse kinematics. A specific reaction chamber was built with large wheels (diameter: 60cm) rotating at 2000 RPM for targets and stripper foils, as well as smaller targets, oscillating stripper foils and elastic scattering target control. The detection chamber contains two MCP's for time-of-flight, two interchangeable implantation x-y Si detectors preceded by a Tunnel of 8 Si detectors and followed by a veto detector. The response, background and efficiency were checked with known reactions and decay chains (Sg isotopes): a background rejection factor of 2×10^{10} and an efficiency > 65 % were obtained.

Recently, a thin ionization chamber has been used in inverse kinematics reactions with a ^{208}Pb beam. The much larger kinetic energy pulse and the TOF provides a mass value. In addition, the IC signal allows us to get a nuclear charge value. Both values are rough but provide additional information on the implanted product. Indeed the identification of transfer products (actinides) through their alpha-chain is ambiguous when their half-life is so short that the alpha signal cannot be distinguished from the implantation signal. The charge signal make it possible to identify them. For a super-heavy nucleus, this direct information on the implanted residue strengthens much its identification via its decay chain. Work is in progress to extend this method to the case of usual kinematics with one single mylar foil: scintillation in a gas provides a signal proportional to the nuclear charge.

Results of planned experiments will be shown and discussed.

Status and future of the RIA project viz. transactinide elements

D.J. Morrissey[1]

[1] Michigan State University, USA

morrissey@nscl.msu.edu

Introduction

The Rare Isotope Accelerator (RIA) is an innovative, large-scale facility that will define the state-of-the-art for the production and use of exotic nuclei. The RIA facility will employ the best features of both projectile-fragmentation (in-flight techniques) and target-fragmentation (ISOL techniques) to provide the widest possible range of exotic nuclei to the nuclear physics community. The project to develop RIA consists of conceptual design as well as research and development studies in many laboratories across the United States. Significant contributions have been made by a very large number of people that, unfortunately, cannot be adequately covered in the present short presentation. In this contribution I will present a brief overview of the RIA facility with an emphasis on the new capabilities for neutron-rich secondary beams.

RIA accelerator

All of the older designs (before the mid-1990's) for the next generation exotic beam facility in the US were based (solely) on the ISOL concept of target fragmentation by light-ion beams (e.g., Nolen [1]). Three important facts emerged during the initial consideration of possible facilities: (A) very sensitive techniques were developed to study nuclear structure with low-intensity fast beams, (B) the limitations from ion-source chemistry on the range of shortest-lived and most exotic nuclei available from ISOL systems were not generally resolved, and most importantly, (C) the IGISOL concept [2], used to thermalize and collection low-energy reaction products, was extended to fast projectile fragments [3,4]. Thus, the scope of the RIA project was increased significantly so that the facility operation would encompass both in-flight and ISOL separation. The optimum production method will be used to produce each secondary beam rather than obtaining those secondary beams available from one or the other technique. This new approach requires the primary or driver accelerator to provide very intense beams of light ions to next-generation ISOL targets as well as intense beams of all heavier stable nuclei to projectile fragment separators. Low energy, target-fragment ions will be extracted from the ISOL targets and accelerated to low energies in the usual way. The high energy, projectile fragments will be delivered to a high-energy experimental arena as well as to a new low energy "ion source" based on new concept of buffer-gas thermalization and reacceleration of projectile fragments. Thus, there will be three different target areas for the primary beam: a set of high power ISOL targets feeding an isobar separator system feeding the low energy accelerator complex, a high intensity projectile fragmentation target with a high resolution fragment separator feeding the high energy complex, and another high intensity projectile fragmentation target with a high acceptance fragment separator connected through a gaseous-ion collector to the low energy complex. The resulting exotic nuclei will be available at four separate experimental regions (ion-source energy, below Coulomb barrier, near Coulomb barrier, and high energy) in order to service a large and diverse user community.

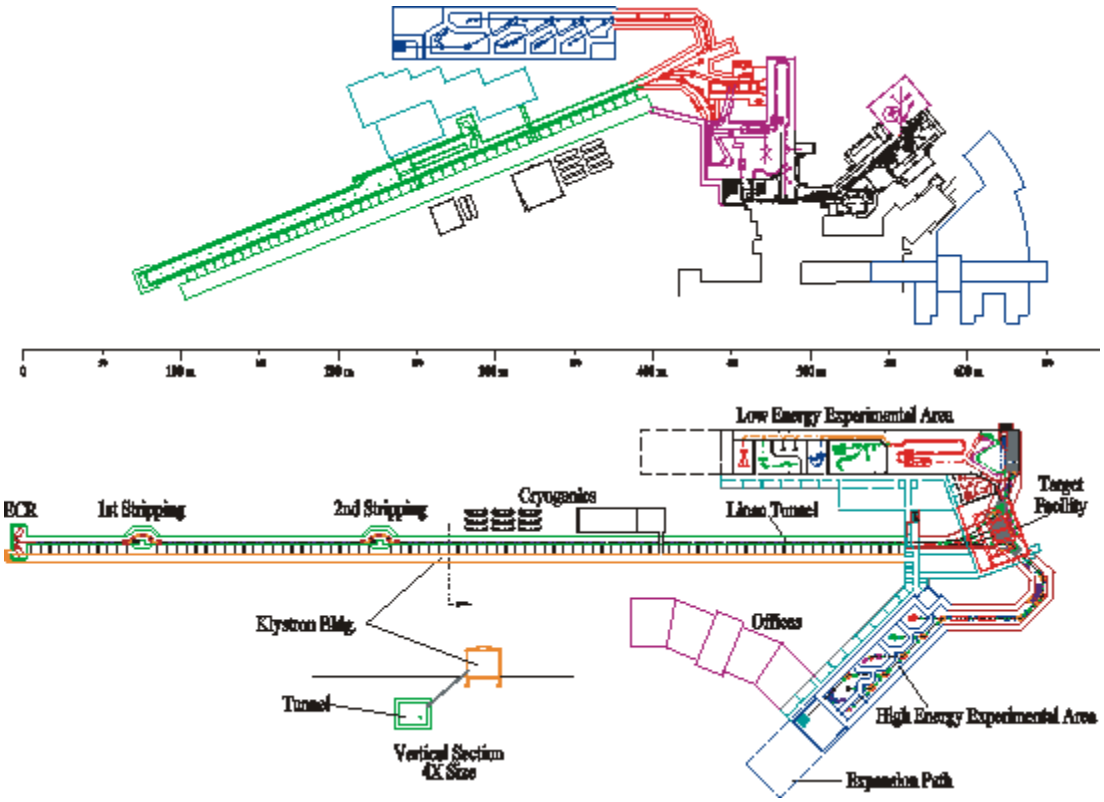

Figure 1. A comparison of the complete RIA facility at the Argonne site (above) and at the Michigan State site (below) at the time of the DoE cost analysis. Both designs contain the same capabilities and experimental areas.

The Nuclear Science Advisory Committee (NSAC) has given RIA the highest priority rating for new construction and has been put forward to the DoE Office of Science as ready for detailed design studies. Preliminary designs for the complete RIA facility have been prepared by the NSCL at Michigan State University and by Argonne National Lab. The schematic layouts of these facilities can be compared in Figure 1. Both layouts are dominated by the layout of the primary linear accelerator that provides beams with E/A ~500 MeV at 400kW up to A~40 and uranium with E/A~400 MeV at 150kW. One difference between the two proposed designs is that the existing ATLAS accelerator is incorporated into the Argonne layout whereas the MSU is a "green field" layout. The technical details of the ion sources, accelerator, target systems, fragment separators, and gas-catchers are being studied in a variety of laboratories around the US. A subcommittee of NSAC has reviewed an independent, bottoms-up cost analysis at the end of 2000. Another DoE panel chaired by Satoshi Otsaki just reviewed the progress on the R&D work in August of this year. An interesting aspect of the RIA accelerator proposed by Ken Shepard and collaborators at Argonne is to have the linac simultaneously accelerate an isotope in multiple charge states to provide very high intensities of the heaviest stable elements. The initial requirements for the experimental facilities and equipment have been prepared by the community [5,6] and have been incorporated into the designs.

Neutron-rich beam production

The neutron-rich beams that will be needed to try new synthetic routes to the heaviest elements will come from either traditional ISOL system or the new ion-collector system. At this point it is too early to

tell which technique will be the most useful but the demands of heavy-element research for the highest beam currents favor the ISOL approach. In the well-known ISOL light primary beams such as protons, deuterons, or ^{3}He beams hit thick production targets closely coupled to ion sources. The raw beams from the RIA ion sources are pre-separated and a small number of beams with nearby masses can be simultaneously delivered to a transport network that includes two high-resolution separators. The monoisotopic beams are then transported to either the low-energy experimental area or to the first stage of the post-accelerator. At present ISOL beam production is carried out with primary beam powers on the order of a few tens of kilowatts. The highest-power ISOL facility (20 kW) presently operational is the ISAC facility at TRIUMF in Canada. Concerted and very specific ISOL R&D work has been carried out for many years in Europe at the ISOLDE facility and elsewhere so that a lot of expertise exists in that community. The biggest challenge for ISOL at RIA is to build target systems that can make use of the order of the extremely high beam power. New ideas have been suggested such as converter systems that accept high-energy deuterons to release high-energy neutrons that go on to induce fission. Substantial R&D is required in order to answer key questions about how traditional and new targets can be build and operated in the ½ megawatt domain. Scaling the beam intensities from the present conditions has been used to obtain the yield predictions for the RIA secondary beams.

Fragment separators have developed significantly over the past decade, see for example [7], so that both of the devices planned for RIA will be next-generation superconducting fragment separators that go well beyond the best present day machines. For comparison, the resolving power and a figure of merit for the A1200 (now retired) and A1900 (recently completed) separators at the NSCL can be compared to the specifications of RIA separators in Table 1.

Table 1. Comparison of ion-optical properties of projectile fragment separators based on superconducting magnets. The resolving power is the dispersion divided by the product of the beam spots size and the magnification in the same coordinate (x). The dimensionless "figure of merit" used to categorize the separators is the product of the relative solid angle ($d\Omega/4\pi$), the momentum acceptance ($\Delta p/p$), and the resolving power.

	$\Delta p/p$ (%)	$d\Omega$ (msr)	$B\rho$ (Tm)	Resolving Power	Figure of Merit
NSCL A1200	+/-1.5	0.8	5.4	2400	0.5
NSCL A1900	+/-2.5	8	6	2900	10.2
RIA High Res.	+/-3	10	8	3000	14.3
RIA High Accpt.	+/-9	10	8	1000	14.3

The new approach for the production of thermalized exotic ions for nuclear structure studies has been pioneered at Argonne and at RIKEN based on ion stopping work at GSI [8]. Moderate [4] and fast [3] nuclear reaction products are stopped in large high-purity helium gas cells and extracted as singly-charged ions through the application of drift fields and gas flow. One of the important ingredients of the new concept is the incorporation of an energy-focusing ion-optical device that can compensate for the large momentum distribution of the projectile fragments. Such devices consist of a dispersive magnetic dipole stage and slowing-down of the fragments in specially shaped energy degraders [8]. The feasibility of momentum compensation, also called range bunching, has been recently demonstrated at the GSI-FRS and recently at Michigan State using pressures near one bar [9]. These results and further calculations have shown that the longitudinal range straggling of typical projectile fragments can be brought down to the level of the intrinsic straggling width of an equivalent monoenergetic beam which is, none the less, on the order of one-half meter of helium gas at one bar. The purity of the buffer gas leading to unwanted ion-molecule reactions has large effects on the efficiency of IGISOL systems as has been shown by the

Leuven group [10]. These neutralization and the many possible effects from the ionization plasma in the buffer gas still has to be fully understood for efficient operation of large-scale gas cells. However, it has been reported that the system operating at Argonne has an efficiency of close to 45% and extraction times below 10 milliseconds [4]. Any upper limit on the rate at which ions can be implanted and efficiently extracted from a large gas cell has yet to be experimentally determined. The total production yields from all of the various techniques have been analyzed by Jiang et al. [11] and various tables and figures are available to check the feasibility of experiments at RIA.

One of the interesting aspects of the study of nuclear reactions induced by radioactive beams is the possibility of using n-rich radioactive projectiles to synthesize new, neutron-rich heavy nuclei. It has been shown by Loveland [12] that new areas in the atomic physics and chemistry of the transactinide elements could be developed using intense n-rich radioactive beams. Various authors have suggested that there will be significant enhancements to the fusion cross sections for n-rich projectiles due to the lowering of the fusion barrier, the excitation of the soft dipole mode and the lowering of the reaction Q values for the more n-rich projectiles. The survival probability of the evaporation residues (EVRs) is also expected to increase due to their reduced fissionability and the lowered excitation energy. There is further speculatation that the use of these projectiles might lead to the successful synthesis of new or superheavy nuclei. Takigawa et al., [13] predict an enhancement of 10^5 in the fusion cross section for the $^{46}K + ^{238}U$ reaction compared to the $^{41}K + ^{238}U$ reaction and an increase of a factor of two in the survival probabilities for the EVRs. Experience from the synthesis of new heavy nuclei by non-radioactive n-rich projectiles shows that an increase of one unit in isospin of the projectile increases the heavy element production cross sections by a factor of 5 [14] so that even small changes in the isospin of the compound nucleus are important.

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The RIA project and heavy element physics

J.A. Nolen[1]

[1] Physics Division, Argonne National Laboratory

nolen@anl.gov

An overview of the U.S. Rare Isotope Accelerator (RIA) Project is given in a companion paper by D.J. Morrissey at this conference. In this paper some specific capabilities of the proposed facility for research on the production and studies of heavy elements will be discussed. First, baseline count rate predictions for sample radioactive beams will be given, and then examples of possible enhancements of these capabilities will be presented.

In recent years there has been much discussion and speculation about the role of radioactive beams in research related to super-heavy elements. This paper will explore the capability of RIA to deliver precise and intense radioactive beams of neutron-rich fission products at Coulomb barrier energies for fusion reactions. The best mechanism for the production of such beams is the 2-step, neutron-generator configuration of the standard ISOL technique. The RIA driver will provide beams of protons, deuterons, or other light ions in the energy regime of 1 GeV with beam powers up to 400 kW. Providing the most intense reaccelerated beams for heavy element research using this method will require optimization of each step in the process. With reasonable assumptions about target, ion source, and post acceleration developments fission fragments near the peaks of the distributions, such as ^{132}Sn and ^{140}Xe, should be available with on-target intensities of 10^{10} to 10^{11} ions per second. The details of the various necessary efficiencies and developments necessary to reach these intensities will be discussed. Possible extensions of the method to intensities above 10^{11}/s will also be considered.

Using radioactive ^{132}Sn on stable targets, compared with stable beams on ^{208}Pb targets, the corresponding compound nuclei have 8 more neutrons at element 118 and 12 more at element 120, for example. Hence, the possibilities of increased production cross sections and longer half-lives of the more neutron-rich isotopes may overcome the 10-100 times weaker beam intensities. New instruments, such as the MASHA spectrograph currently being commissioned in Dubna, may be well suited to studies with radioactive beams such as the ones mentioned above. The post-accelerator RIA will also be able to provide intense CW beams of stable ions for measurements complementary to those with radioactive beams.

Research supported by the U. S. Department of Energy under contract W-31-109-ENG-38.

Synthesis and mass determination of heavy and superheavy nuclei at separator VASSILISSA

A.V. Yeremin[1], Y.T. Oganessian[1], A.G. Popeko[1], O.N. Malyshev[1], A.V. Belozerov[1], V.I. Chepigin[1], M.G. Itkis[1], A.P. Kabachenko[1], R.N. Sagaidak[1], A.V. Shutov[1], A.I. Svirikhin[1], S. Hofmann[2], S. Saro[3]

[1] Joint Institute for Nuclear Research, Russia
[2] Gesellschaft fuer Schwerionenforschung, Germany
[3] Comenius University, Slovak Republic

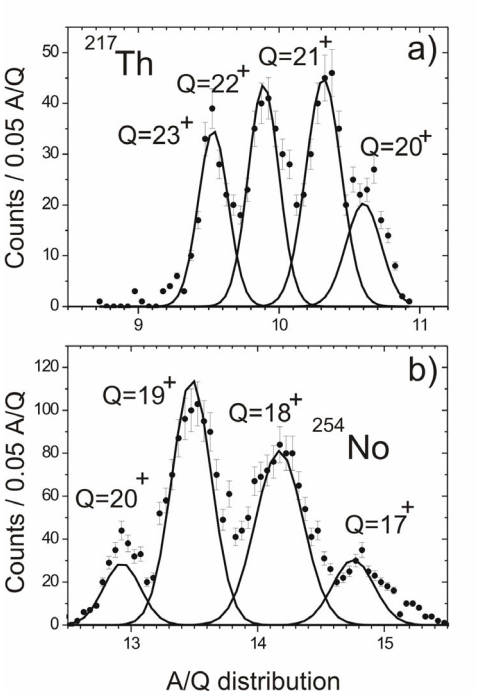
eremin@sunvas.jinr.ru

One of the criteria of the quality and reliability of the experimental results in the field of the synthesis of superheavy elements (atomic number $Z \geqslant 110$) is the reproducibility of the obtained data. Because the cross section values for the synthesis of elements with $Z \geqslant 110$ are at the level of picobarns and even lower it results in possible detection of one nucleus per few weeks using the presently available techniques. Another limiting point in attempts to reproduce presently obtained results is the problem of exact reproduction of the beam energy at the half - thickness of the target. The deviation of the beam energy of 1 % (typically 2 - 3 MeV) could lead to the reduction factor of 2 - 3 and to make the recurring ineffective. Until now only few experiments could be mentioned as successful repetition of previously obtained results. First are the experiments at the velocity filter SHIP aimed to the conformation of the synthesis of the isotopes ^{272}111 and ^{277}112 made earlier with the use of the same experimental set-up [1]. And second are the experiments performed at RIKEN with gas filled separator GARIS successfully repeated SHIP group experiments on the synthesis of the isotope ^{271}110 [2].

The study of the decay properties and formation cross sections of the isotopes of elements 110, 112 and 114 was performed employing high intensity ^{48}Ca beams and ^{232}Th, ^{238}U, ^{242}Pu targets [3,4,5] and the electrostatic separator VASSILISSA [6] during the years 1998 - 1999. At beam energies corresponding to the calculated cross section maxima of the 3n evaporation channels the isotopes ^{277}110, ^{283}112 and ^{287}114 were produced and identified (see also [7]).

Aiming at the continuation of the experiments on the synthesis and study of decay properties of superheavy nuclei with the use of accelerated ^{48}Ca beams and at the increasing the identification ability of the experiments the separator VASSILISSA was upgraded. For that purpose a new dipole magnet, having a deflection angle of 37 degrees, was installed behind the separator VASSILISSA replacing the old 8° magnet. The new magnet provides an additional suppression of unwanted reaction products and a possibility to have the mass resolution at the level of 1.5 -2 % for heavy nuclei with masses of about 300 amu.

The VASSILISSA separator with the new dipole magnet was tested with a number of heavy ion induced complete fusion reactions [8,9]. The evaporation residues produced in reactions of ^{40}Ar bombarding ions with ^{164}Dy and ^{208}Pb targets and of ^{44,48}Ca ions with ^{174}Yb, ^{198}Pt, ^{204,206,208}Pb targets were used in the analysis. Using ER - α and ER - SF correlation analysis for detected ER's TOF and strip number (that corresponds to the certain value of Bρ) were evaluated. Together with known value of magnetic field B of magnetic analyzer it was possible to evaluate A/Q values and for known A the charge distributions for investigated nuclei can be extracted. The results obtained for A/Q distributions of the ^{217}Th and ^{254}No ER's are shown in the following figure.



The first planned experiment in the field of superheavy elements with the use of upgraded separator was aimed to the synthesis of the isotope $^{283}112$. It was the first experiment with ^{48}Ca beams in 1998, focused to the synthesis of heaviest elements, and it became the basis for all other search experiments for synthesis elements with Z=114 - 118. An additional reason was the fact that the non-observation of any events in the reaction $^{48}Ca + ^{238}U \rightarrow ^{283}112^*$ studied with the BGS separator at Berkeley at the beam energy $E_{1/2}$=231 MeV in the half - thickness of the target was reported in [10].

Enriched ^{238}U (99.999 %) material was used for the preparation of the targets. The projectile energy was varied by extracting the beam from an appropriate radius of the cyclotron. The beam energy was determined by measuring the energy of the ions scattered at 30^0 in a thin (200 μg/cm^2) Au foil and with a time-of-flight technique. Beam energy values measured by both methods coincide within an interval of ± 1 MeV (± 0.5 %). An accuracy of the determination of the beam energy absolute value was tested using a magnetic spectrometer MSP144 and was about 0.5 % at the level of 243 MeV. The measured energy spread of the scattered ions was 1 % (FWHM).

At a beam intensity of $4 \cdot 10^{12}$ ions·s^{-1}, the total counting rate of all events at the focal plane detectors was 5 - 10 s^{-1}. The counting rate at a single strip in a position interval of 1.0 mm amounted to the following values; for the α - like signals (in the absence of signals from the TOF detectors) with an energy higher than 5.5 MeV - less than 0.075 h^{-1}; for the α - like signals with an energy of 0.5 - 5 MeV (signals corresponding to escaped α particles) - about 0.2 h^{-1}; for recoil - like (ER - like) signals (with a TOF signal) with an energy higher than 5 MeV and time of flight corresponding to heavy ER's (70 - 90 ns) - less than 0.1 h^{-1}.

After preparatory experiments, irradiation of the U target started at the beam energy $E_{1/2}$=230 - 231 MeV in the middle of the target, which is close to that used in the previous experiment [3]. During a period of 29 days a beam dose of $5.91 \cdot 10^{18}$ projectiles was collected. No SF events were detected during this irradiation. In addition, possible decay chains of the ER $\rightarrow$ $\alpha \rightarrow \alpha 1 \rightarrow \alpha 2$ type were searched for within time intervals 5 μs < t < 1000 s and 8 MeV < E_α < 13 MeV. Signals from α decay could be missed only in the case when an α particle escaped through the open front side of the detector array (30 % probability) or when the lifetime was shorter than 2 μs and the decay occurred in the dead time of the

data acquisition system. The windows for the relative positions were twice as much as the resolution at FWHM. No such decay chains were found for the irradiation at the beam energy $E_{1/2}$ =230 - 231 MeV. The upper cross-section limit obtained at this energy is 2.25 pb at a probability level of 68 %.

Then the energy of bombarding ions was increased up to $E_{1/2}$=234 MeV, resulting in the excitation energy of the compound nucleus ^{286}112 E*=35 MeV. During a period of 15 days a beam dose of $4.68 \cdot 10^{18}$ projectiles was collected. Two events from spontaneous fission were detected in this irradiation at the higher beam energy. Both SF events were characterized by a coincident event of higher energy signals (52 and 130 MeV) in the stop detector and lower energy signals (13 and 40 MeV) in the backward detectors. Correlation analysis of the possible decay chains of the ER $\rightarrow \alpha \ldots \rightarrow$ SF type with the upper limit of the time intervals t of up to 10,000 s resulted in two ER - SF correlations. The position difference determined from the ER and SF signals was 0.6 mm for the first event and 0.8 mm for the second one. Time intervals ΔT=180.5 sec and 1459.5 sec., respectively, were measured. The probability that the first correlation is a chance event is 0.005, for the second SF-event the corresponding probability is 0.038.

We attempted to identify SF activities observed in the ^{48}Ca + ^{238}U reaction using mass determination with the 37° dipole magnet. Using ER - SF correlations, positions of the implanted ER's and corresponding TOF's were extracted. The most probable atomic mass values for the most probable charge states were found by solving a system of equations for A/Q values by the maximum likelihood method. For the first event a corresponding ratio A/Q=16.0 and for the second one A/Q=16.679. The values A=288.0 (Q=18) and A=283.5 (Q=17) for the first and second events were obtained. We estimated the accuracy of mass measurements to be about 2 %. Mean value of the masses for two detected nuclei amount <A> 285.7 ± 5.7. Cutting down the upper limit by the mass of compound nucleus A_{CN}=286, mass interval from A=280 to A=286 could be obtained. This result indicates, first of all, that the observed nuclides belongs to the region of superheavy nuclei and their masses are close to the expected masses of the evaporation products of the reaction ^{48}Ca + ^{238}U. Due to the relatively low excitation energy of compound nucleus E_{CN}^* ≈ 35 MeV the evaporation of charge particles (protons or α particles) is strongly prohibited, more probable that the events measured in this work belongs to the isotope ^{283}112 produced via a 3n evaporation channel in the reaction ^{48}Ca + ^{238}U $\rightarrow$ ^{286}112*.

The mean value of the two measured time intervals together with four previously measured events [3,4] results in a half-life $T_{1/2} = 307^{+212}_{-89}$ s which coincides well within error bars with reported earlier values [3,4]. The cross-section evaluated for the production of two fission events at a beam energy of 234 MeV in the half-thickness of the target is 3^{+4}_{-2} pb that coincides well in error intervals with reported earlier values obtained with the separator VASSILISSA [3] (5^{+6}_{-3} pb) and in the experiment aimed at the determination of chemical properties of element 112 performed at Dubna in 2001 [11], were 8 SF events were detected, that corresponded to the cross-section $2^{+0.9}_{-0.7}$ pb. In February - March 2003 the experiment aimed to the determination of chemical properties of element 112, synthesized in the reaction ^{48}Ca + ^{238}U, was performed at GSI Darmstadt [12]. Few SF events were detected that corresponded to the cross-section in the range of 1 – 5 pb and is in good agreement with results, obtained with VASSILISSA separator and chemical experiment at Dubna.

The deviation of the beam energy value at which the events were obtained during this experiment and the reported 5 years ago value [3] could be explained by the fact that an accuracy of the absolute values of beam energy measurements 5 years ago was not tested and deviations could be at the level of 1 - 1.5 %, i.e. 2.5 - 3.5 MeV, and/or by the fact that in the past experiment 1.6 mg/cm^2 Al backing foils were used for the target support (about 25 MeV energy losses for ^{48}Ca beam with an energy of about 5 A·MeV) whereas now 0.74 mg/cm^2 Ti backing foils were used (about 10 MeV of energy losses).

The obtained results of mass measurements of heavy ER's allow one to exclude transfer products and incomplete fusion products and to assign the two observed SF events to the complete fusion of ^{48}Ca + ^{238}U with a high probability. The non-observation of α decay, the improbable evaporation of protons or α particles from the compound nucleus and the relatively low excitation energy of 35 MeV let us assign the

fission events measured in this work to the isotope $^{283}112$ produced via the 3n evaporation channel in the reaction $^{48}Ca + ^{238}U \rightarrow ^{286}112^*$.

The non-observation of any events in the reaction $^{48}Ca + ^{238}U \rightarrow ^{286}112^*$ at the beam energy $E_{1/2}$ =231 MeV [8] can be explained by the fact that the beam energy was too low and corresponded to the left side of the excitation function, in which a decrease in the cross section value is very sharp.

Acknowledgments

This work was performed partially under the financial support of the Russian Foundation for Basic Research, contract N 02-02-16116 and JINR – BMBF (Germany), JINR - Polish, JINR - Slovak Cooperation Programs.

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Spectroscopy of the transfermium nuclei ^{251}Md

A. Chatillon[1]

[1] CEA Saclay, France

chatillo@hep.saclay.cea.fr

The study of very heavy nuclei beyond the Fermium isotopes has attracted a strong interest in recent years. Due to the strong Coulomb repulsion, these nuclei are only stabilized by shell effects. After the first successful studies of even-even nuclei where collective properties have been deduced, the spectroscopy of odd-A isotopes is the next step needed to understand the single-particle properties in this mass region. Due to the relatively high cross section, the nucleus ^{251}Md is the best odd-Z candidate.

In order to study the nucleus ^{251}Md (Z=101), three experiments have recently been performed at the university of Jyväskylä: by prompt electron spectroscopy using the electron detector SACRED, by prompt gamma spectroscopy with the new JUROGAM array, and by alpha, electron and gamma spectroscopy after the alpha decay of ^{255}Lr using the GREAT detector. The first results of these experiments will be presented.

Experimental study on photofission of ^{242}Pu, ^{238}U, ^{235}U and ^{232}Th in giant dipole resonance region

T.D. Thiep[1], N.V. Do[1], N.N. Son[1], T.T. An[1]

[1] Institute of Physics, Hanoi, Vietnam, Vietnam

tthn@netnam.org.vn

Photofission represents a powerful tool for investigating the double humped fission barrier of actinide, especially for studies on shape isomer, formed by photonuclear reactions. In general, photofission seems to be favourable for investegation of the nuclear structure as in the case electromagnetic interaction is well - known and the theoretical consideration is simplified. Due to the missing Coulomb barrier compound states of low excitation energy are easily populated. The main advantage, however, is spin selectivety of the electromagnetic interaction leads to the favoured excitation of the few specific fission channels compared with particle induced reactions. The giant electric dipole resonance dominates the photoabsorption cross - section in most important energy range (i.e in giant dipole resonance region).

In photofission the mass and charge distributions and the isomeric ratios of fission fragments are ones of the most interesting observables as their parameters can be related to the dynamics of the fission process. For the reasons, we have concentrated our investigations in these characteristies.

In our investigations for photon sources we used electron accelerators of microtron type. Microtrons are high intense photon sources therefore they are suitable for the studies of photonuclear reactions where the reaction cross-sections are small. The targets after irradiation were measured by direct gamma spectroscopic technique without any chemical separation.

Target preparation, irradiation and measurement: We have carried out photofission of Pu242, U235, U238 and Th242. Our first studies were photofissions of Pu242 and U235 started in 1982 at the Joint Institute for Nuclear Research, Dubna, Russia by using microtron MT - 22 (its maximum bremsstrahlung energy can be varied stepwise from 10 to 22 MeV). By that time the data on photofission of Pu242 have not been published, so our results can be considered as first ones.

The target of 3 (+ or -) 0.3 mg of dioxide Plutonium enriched to 94.7% Pu242 was prepared on a 70 micro metters thick aluminium disc of 55 mm diameter. The active layer had a diameter of 20mm. For photofission of U235, the target of 30mg dioxide uranium enriched to 97% U235 was used in the experiment. The plutonium was irradiated for 5 and 6 hours with 18.1 and 20.7MeV bremsstrahlungs respectively. The U235 target was irradiation for 5 hours with 18.1MeV bremsstrahlung. In order to avoid thermal neutron induced fission of U235 the target was packed by Cd envelope of 0.5mm thickness and fast neutron induced fission is less than 0.2% can be negled. For both the Pu242 and U235 targets the catcherfoil technique was used for collecting fission fragments. The catcherfoil which consisted of 0.1mm thick very pure aluminium foil (purity of 99.99%) was placed at a distance of 1mm from the Pu242 and U235 targets and then was measured with high energy resolution semiconductor detector.

The photofissions of Th232 and U238 were performed with 15 MeV bremsstrahlung produced by microtron MT-17 of the National Institute of Physics, Hanoi by 4 hours irradiations. The target of U238 was an amount of 18mg U3O8 enriched to 99.6% U238 prepared on a 0.5mm thick high pure aluminium disk of 20mm in diameter and the target of Th231 was a pure Th sample having diameter of 20mm, thickness of 0.5mm and density of 15mg/cm2 wrapped in a thin layer of lapsan on 1mm thick pure aluminium disk. The targets after irradiations were measured with direct gamma spectroscopic technique without any chemical separation.

For measuring gamma spectra of photofission fragments two spectrscopic systems were used. At the National Institute of Physics, Hanoi, the targets were measured by a spectroscopic system consisted of 62 cm3 coaxial HPGe detector ORTEC with a resolution of 2.1 KeV at 1332 KeV gamma ray of Co60, a spectroscopic amplifier CANBERRA mode 2001 and a 4096 channel analyzer mode ND-66B, Nucl. Dat. Inc. coupled with a PDP 11/23 computer for data processing. At the Joint Institute for Nuclear Research, Dubna the measuring system consisted of a 45 cm3 Ge(Li) detector, a NOKIA spectroscopic amplifier, a 4096 channel analyzer NOKIA, model LP-4096 was used.

Mass distributions: The relative comulative yields for the fission fragments were determined from successive measurements of gamma fission spectra from the catcherfoils and the target. The relative total yields for a given mass chain were obtained from the relative yields by making correction with the expression for charge distribution. The absolute product yields were obtained by normalization to 200% the area under the total mass distribution.

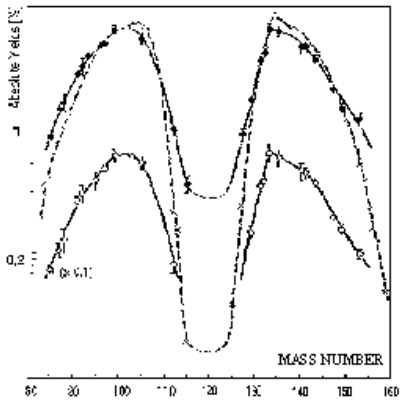

Fig.1. Mass distribution for photofission of Pu^{242} with 20.7 (•) and 18.1 MeV (o) bremstrahlungs, (x) Fission of Pu^{241} with thermal neutrons.

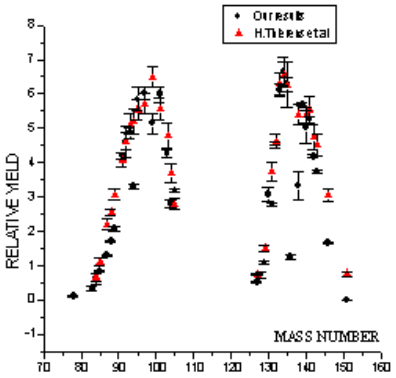

Fig.2. Mass distribution for photofission of U^{238} with 15 MeV bremstrahlung.

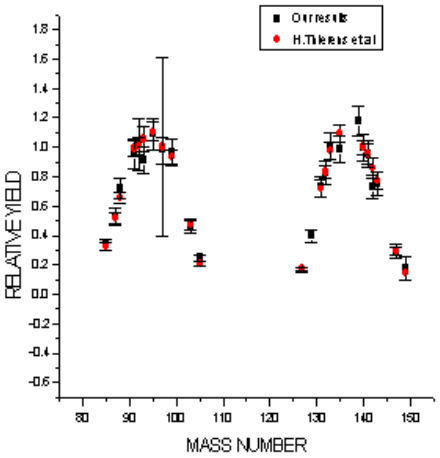

Fig.3. Mass distribution for photofission of U^{235} with 18 MeV bremstrahlung

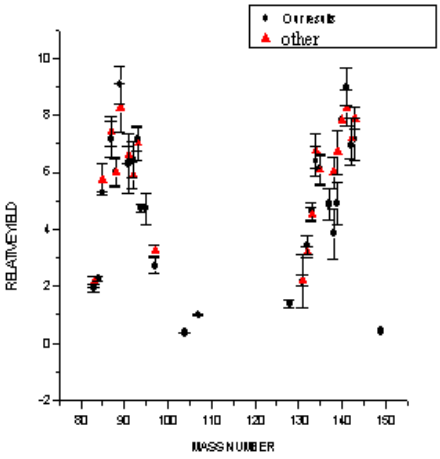

Fig.4. Mass distribution for photofission of Th^{232} with 15 MeV bremstrahlung radiation

Our experimental results are shown in fig.1, 2, 3 and 4. We have obtained for the Pu242 photofission 25 mass chain. We can see in fig.1 a weak fine structure in mass region 133-135 due to the close neutron shell N=82. For the case of U235 photofission 34 product yields were obtained. For U238 the comulative yields for 44 mass chains have been determined. A fine structure in the mass regions 133 - 135 and 140 - 142 was observed and our results are compared to those of De Frenne et al. For Th232 38 comulative mass yields have been established. Our results are compared to that obtained by other groups and fine structure is exhibited.

Charge distribution: We have studied the charge distribution for the photofission of U238 with 15 MeV bremsstrahlung. Most of experimental data on photofission charge distribution were obtained from independent yields which were determined using chemical separation or by direct gamma spectroscopic method. In practice there are very small number of mass chain where it has been possible to determine the independent yields of more than one isobar. The data on independent yields for any photofission system available in the literature are very scarce. In the case of U238 photofission the Zp values lie too far from the beta - stability line. So that in a given mass chain, the isotopes produced with the highest probability have very half - lives, making the measurements of these gamma spectra very difficult. We compromise by assuming that information about charge distribution can be obtained from comulative yields for products lying far enough away from the line of beta - stability. The charge distributions for mass chains 95, 97, 99, 128, 130, 131, 132, 134, 135, 138, 140 and 141 were investigated. We deduced from comulative (or independent) yields the most probable charges Zp for 7 other mass chains based on two methods namely the unchanged charge distribution and the emperical relation.

Fission fragment isomeric yield ratios As it is known in fission the independent isomeric ratios are measure of the primary fission fragment angular momentum. Isomeric yield ratio can be determined if the isomeric pair are screened product, i.e, if the product can be formed only directly in fission process. Up to now the studies on the independent isomeric yield ratios in the photofission of U238 are very limited. In our investigation we succeeded in determining the isomeric yield ratios for the following pairs Sb128m - Sb128m, I132m - I132g and Xe135m - Xe135g.

Beside the above mentioned studies we have also developed the statiscal model to predict independent yields and pairing effects which are in good agreement with experemental data. Recently we have applied successfuly the multimodal fission model to analyze the mass distribution in fission at low excitation energies.

At the presents time we are investigating spontaneous fission and photofission of transactinide element 96Cm. The results will be published in near future.

This report has been completed with the financial support of the Vietnam National Program in Natural Science, project N: 430201. The authors would like to express their sincere thanks for this precious assistance.

Synthesis of new heavy nuclei using RNBs

W.D. Loveland[1], M. Cloughesy[1]

[1] Oregon State University, USA

lovelanw@ucs.orst.edu

In proposing new radioactive beam facilities, such as the RIA facility, the issue arises as to the potential for synthesizing new heavy nuclei using radioactive nuclear beams (RNBs). While it is tempting to write several interesting possibilities, we believe that one must make quantitative estimates of the realistic probability of such studies. Accordingly, we have quantitatively evaluated the possibilities of synthesizing heavy nuclei using the proposed RIA facility.

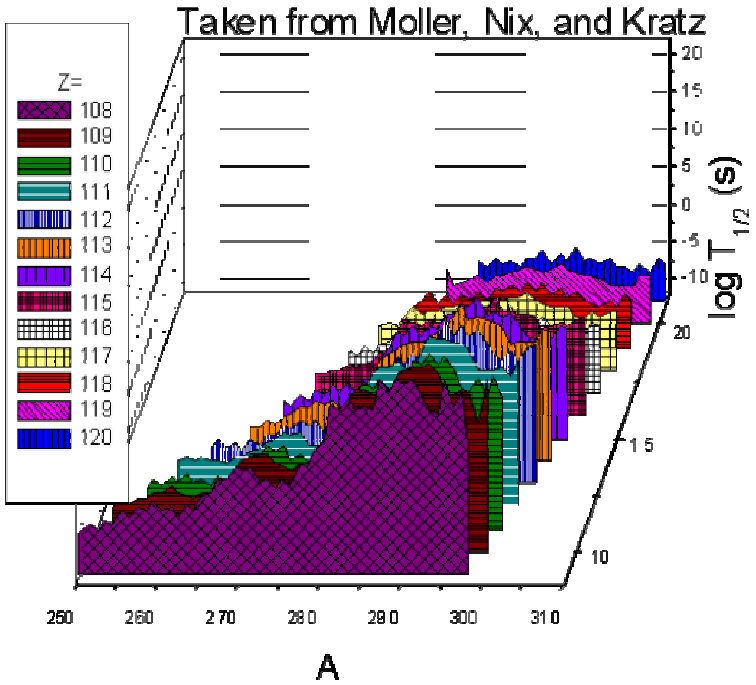

Figure 1. Variation of calculated [1] half-lives of heavy nuclei with Z and A.

We begin by noting the potential value of n-rich beams in synthesizing heavy nuclei (Figure 1). In Figure 1, we show a plot of the calculated half-lives [1] of the heavy nuclei sorted by Z and A. Note that in addition to the expected increases in half-life at the magic numbers N=162 and N=184, one sees a general overall increase in half-life with increasing neutron number. This increase amounts to an increase of orders of magnitude in half-life, that could qualitatively change the character of the studies of the atomic physics and chemistry of these elements. We would also expect that the lowered fusion barriers for the n-rich projectiles might lead to lower excitation energies and greater survival probabilities.

What we have done to examine the possibilities of synthesis of new nuclei using the RIA facility is to do a brute force calculation. We have taken the RIA beam list [2] that gives the identity and intensity of all the expected RNBs that have suitable energies (<15 A MeV) and considered all possible combinations of these projectile nuclei with all "stable" target nuclei (including radioactive actinide nuclei) with appropriate target thicknesses (~0.5 mg/cm^2). All reactions are assumed to take place at a projectile energy equivalent to the Bass barrier [3]. The fusion probability is calculated using a semi-empirical

formalism developed by Armbruster[4] that considers fusion hindrance and assumes fusion to be primarily an s-wave process. Γ_n/Γ_f values used to evaluate the survival probabilities are taken from our semi-empirical systematics of Γ_n/Γ_f [5]. For the most promising cases, the fusion probability was re-calculated using the HIVAP computer code [6]. The yield of each projectile-target combination was evaluated in atoms/day.

This formalism was checked by calculating the cross sections of the formation reactions used to synthesize elements 104-112 and comparing them to the observed cross sections. The results (Figure 2) show an agreement between predicted and observed cross sections within an order of magnitude for cross sections ranging over seven orders of magnitude.

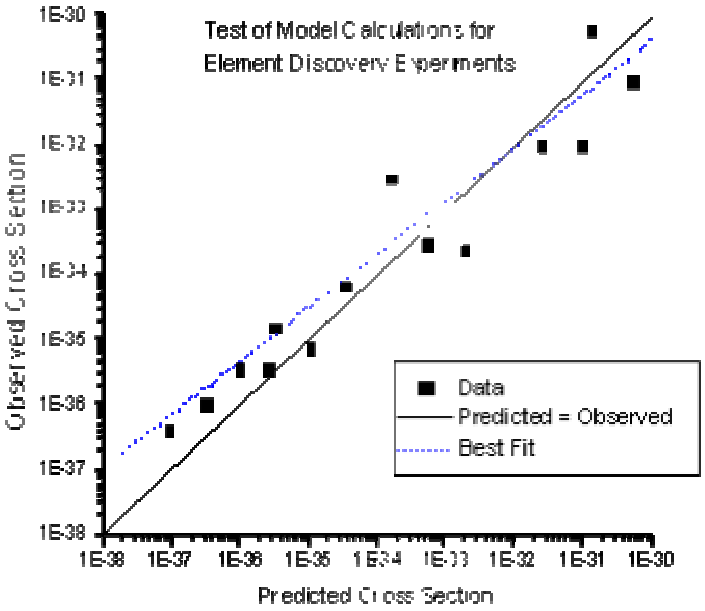

Figure 2. Comparison of observed and calculated formation cross sections for elements 104-112.

The RIA facility appears to offer significant opportunities for the study of the atomic physics and chemistry of the heaviest elements (Figure 3). It appears possible to synthesize significant numbers of very n-rich isotopes of elements 104-108 (Rf-Hs). Because these nuclei have very long half-lives, qualitatively different studies of these nuclei should be possible. These hot fusion reactions typically involve radioactive nuclei that are not far from stability. This is due to the higher fluxes of these nuclei compared to the more exotic projectiles.

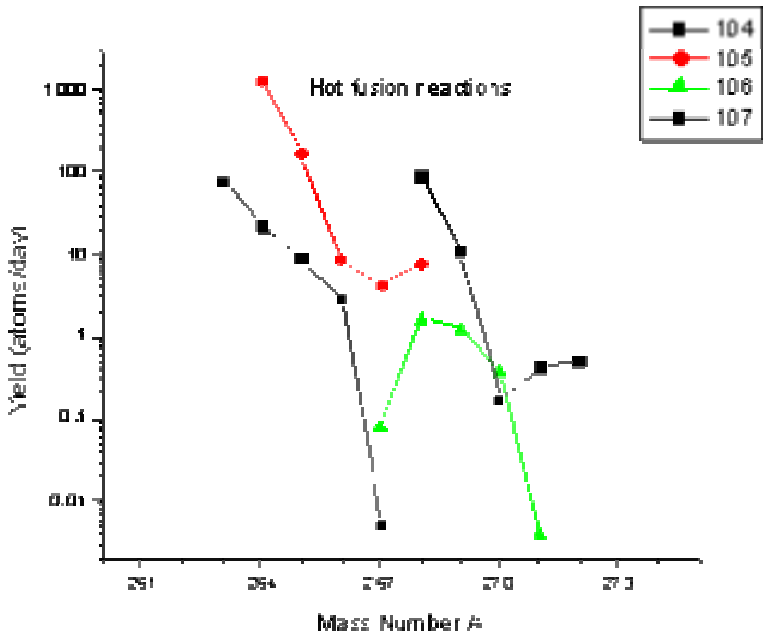

Figure 3. Production rates of n-rich isotopes of elements 104-108 using the RIA facility.

The situation regarding the synthesis of new heavy elements is mixed (Figure 4). While it is possible to make new elements using radioactive beams, the use of stable beams gives higher production rates. (In the stable beam calculations, we have assumed 0.3 pWa beam currents.)

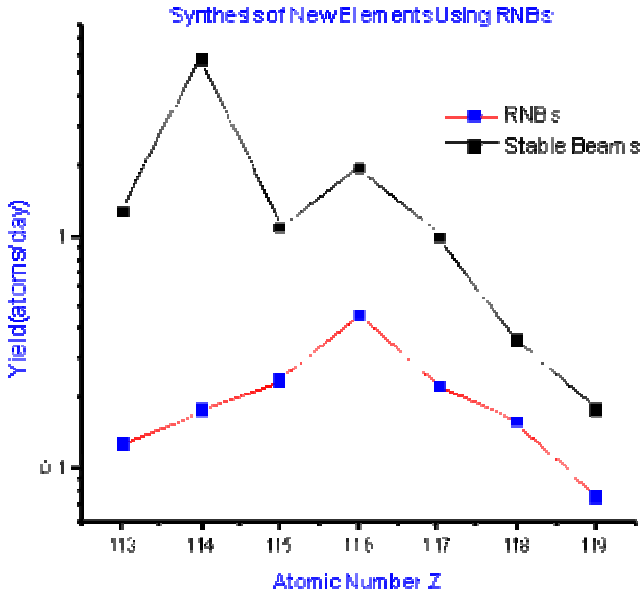

Figure 4. Production rates of new elements using radioactive beams from RIA and stable beams.

The radioactive projectiles lead to more n-rich nuclei than the stable projectiles (Figure 5) which may be important for the study of the nuclear structure of the heaviest elements. One might inquire why the

conventional cold fusion reactions do not play a more important role in these simulations. The product of the cross section and available flux is not sufficient to give suitable production rates.

It should be noted that these estimates of production rates do not include any fusion enhancement effects, other than the lowering of the fusion barriers (and excitation energy) with the n-rich projectiles. This is based upon the experimental studies of fusion with n-rich radioactive beams [9,10].

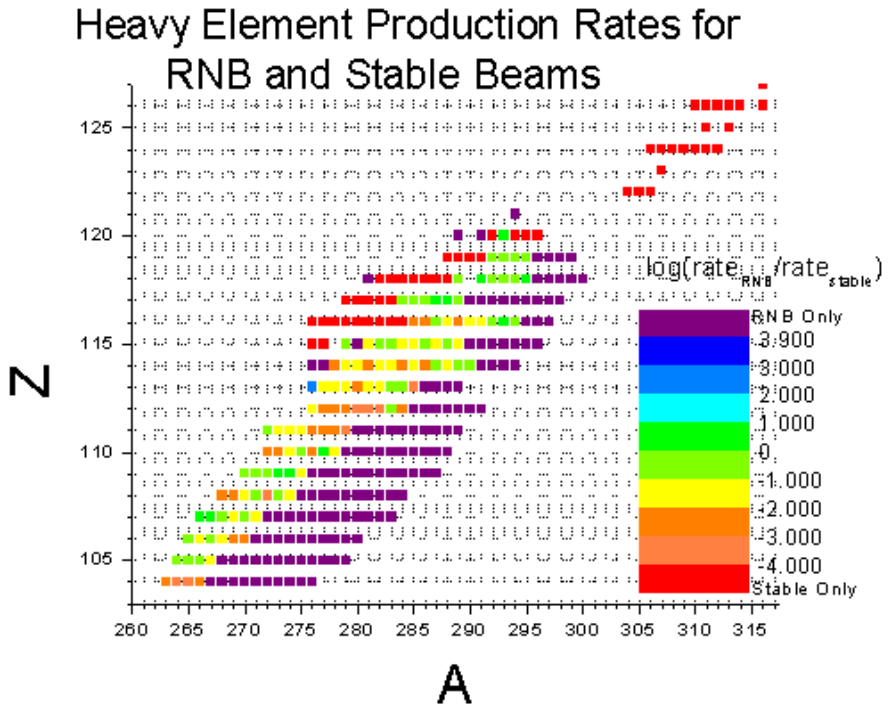

Figure 5. Comparison of production of heavy nuclei with RIA beams and stable beams.

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Novel isomer spectroscopy and quasiparticle configurations in ^{254}No

G.D. Jones[1] for the Anglo-Finnish-French S.H.E. collaboration

[1] University of Liverpool, United Kingdom

jx@ns.ph.liv.ac.uk

The recently installed GREAT [1] focal plane detector system (with triggerless data acquisition) has been coupled to the gas filled recoil spectrometer RITU at the University of Jyväskylä, Finland, for a study of long-lived isomer decays. The ^{172}Yb(^{48}Ca,4n)^{216}Th reaction at a beam energy of 217 MeV has been used as a 'proof of principle' experiment to verify some new techniques which have been proposed [2] for focal plane isomer spectroscopy. The basic method is a variation on the recoil decay tagging (RDT) technique, by which position-time correlations are performed for recoils, isomer-delayed summed electron conversion transitions and alpha decays at the same position of a multi-pixel, double-sided strip detector. The nucleus ^{216}Th has a long-lived isomeric state [3] with $T_{1/2}$ much greater than 1μs, (which is the approximate transit time of recoils through RITU), followed by an alpha decay of ~25ms ; ideal for the present application. The production cross section is also an order of magnitude larger than that for super heavy elements. The summed electron conversion pulse has been observed in coincidence with γ-rays produced from unconverted transitions in the isomer decay path. The cross section ratio of isomer to prompt decays has been obtained by comparison with RDT events where a summed electron conversion pulse was not present in the position- time correlations. The ^{208}Pb (^{48}Ca,2n)^{254}No reaction has been studied at 219 Mev beam energy, in a similar manner, to obtain, for the first time, the excitation energy and decay path of a long-lived isomer [4] in ^{254}No, which was inferred about 30 years ago. In view of the inherent difficulties, at the present time, associated with the elucidation of single quasiparticle (qp) configurations in odd mass nuclei in this region, the structure of isomeric states may be crucial to our understanding of single particle orbitals in the spherical shell model. An isomer's qp configuration, populating intruder orbitals in the deformed mean field, allows one to deduce their origins from the expected doubly magic, spherical shell model states around A=300. The possible qp configurations of this isomeric state will be discussed.

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Investigation of the 5n and α4n channels in the ^{20}Ne on ^{244}Pu reaction

R. Dressler[1], B. Eichler[1], D. Piguet[1], R. Eichler[1,2], H.W. Gäggeler[1,2], F. Haenssler[2], S. Soverna[2], M. Schädel[3], E. Schimpf[3], K. Eberhardt[4], P. Thörle[4], N. Trautmann[4]

[1] Paul Scherrer Insitut, CH-5232 Villigen PSI, Switzerland
[2] Departement für Chemie und Biochemie, Universität Bern, Freiestrasse 3, CH-3012 Bern, Switzerland
[3] Gesellschaft für Schwerionenforschung mbH, Planckstrasse 1, D-64291 Darmstadt, Germany
[4] Institut für Kernchemie, Universität Mainz, Fritz-Strassmann-Weg 2, D-55128 Mainz, Germany

rugard.dressler@psi.ch

The isotope ^{259}Rf was firstly investigated by Flerov et al. [1] in the 5n channel of the reaction ^{22}Ne on ^{242}Pu. Two years later Zvara et al. [2] published first ever chemistry experiments with the element Rf (Z=104) based on the products of the same nuclear reaction. These experiments were several times repeated and controversially discussed by different authors in the next two decades (for a nearly complete compilation of these discussions see [3]). Flerov et al. showed in [1] in addition to the excitation function of ^{259}Rf the low energy part of the excitation function of ^{256}No, which is produced in the α4n channel of the reaction ^{22}Ne on ^{242}Pu.

Later, only a few experiments were made to investigate nuclear reactions based on Pu and Ne [4, 5]. In our experiments we will continue the investigation of xn and αxn reactions in the region of Rf and No, which was started already in [5]. The intention is to study formation and decay properties of ^{259}Rf and ^{256}No in the reactions ^{244}Pu(^{20}Ne, 5n) and ^{244}Pu(^{20}Ne, α4n), respectively.

^{259}Rf has a half-life of (3.2±0.6) s and decays with (92±2)% probability by emission of α-particles of 8.77 MeV and 8.87 MeV [6]. ^{256}No with a half-life of (2.91±0.05) s decays also via emission of α-particles of 8.448 MeV and 8.402 MeV [6] with a (99.47±0.06)% branching ratio. For both nuclides a spontaneous fission decay mode was reported.

A Pu target (enriched 98.6% in ^{244}Pu) with a thickness of about 0.5 mg/cm^2 is in preparation at the University of Mainz via molecular plating of its nitrate on a Be-backing of 12 μm thickness.

In a first experiment at the PSI Phillips cyclotron this target will be bombarded with ^{20}Ne^{6+}, at a beam energy of 113 MeV.

The recoiling reaction products are swept out of the recoil chamber using a He-carbon-gas-jet and transported to the PSI Tape System [7] within 3 s. The aerosols are collected by impaction in vacuum on the magnetic tape during 2 s and subsequently the samples are moved in front of 8 consecutive α-PIPS-detectors (450 mm^2 active area). For the event-by-event recording the data acquisition system described in [8, 9] will be used.

In Figure 1 the excitation function given in [1] is compared with model calculations using the HIVAP code [10, 11]. Under the described experimental conditions about 15 events of ^{259}Rf at a cross-section of 0.6 nb will be expected within an 8 day irradiation at beam intensities of about 1.2 eμA. The use of the PSI Tape System inhibits the accumulation of long-lived spontaneously fissioning nuclides, such as ^{256}Fm, which are produced in transfer channels of the nuclear reaction. But the outcome of the experiment also depends very much on the purity of the target material, since by-products (e.g. $^{211-214}$Po) from nuclear reactions with heavy metal impurities in the target may disturb the unambiguous identification of ^{259}Rf and ^{256}No. In that case a fast chemical separation as described in [12] will be necessary.

The results of this first experiment, which is conducted in August 2003, will be presented.

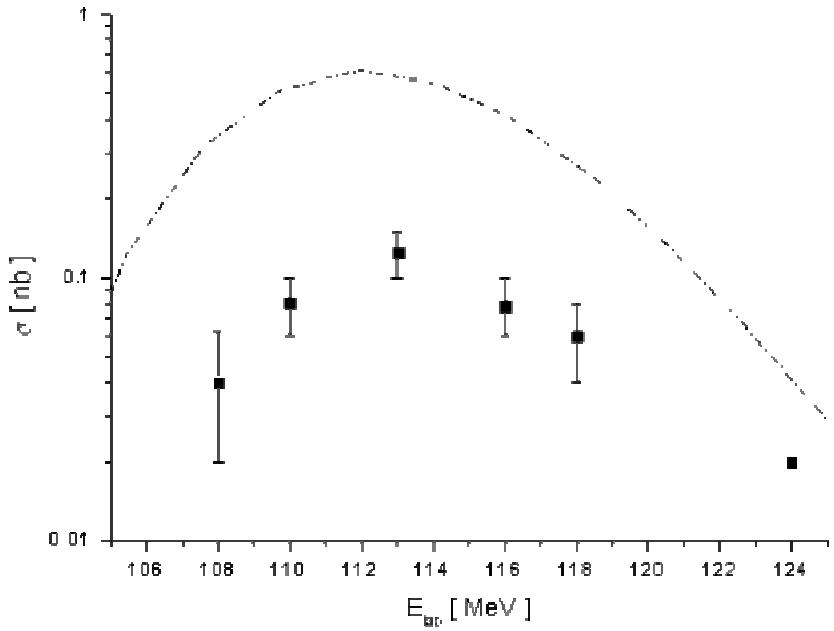

Figure 1. The cross section of ^{259}Rf in the reaction ^{242}Pu(^{22}Ne, 5n). Symbols: experimental data from [1]; dotted line: model calculations using HIVAP for the reaction ^{244}Pu(^{20}Ne, 5n).

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The search for ^{271}Mt via the reaction ^{238}U + ^{37}Cl

P.M. Zielinski[1,2], K.E. Gregorich[1], Ch.E. Düllmann[1,2], C.M. Folden III[1,2], P.K. Gupta[1,2], D.C. Hoffman[1,2], W. Loveland[3], H. Mahmud[1], D. Peterson[3], M. Schädel[4], J.M. Schwantes[1,2], R. Sudowe[1,2], H. Nitsche[1,2]

[1] Lawrence Berkeley National Laboratory, Berkeley, USA
[2] University of California, Berkeley, USA
[3] Oregon State University, USA
[4] GSI, Germany

PMZielinski@lbl.gov

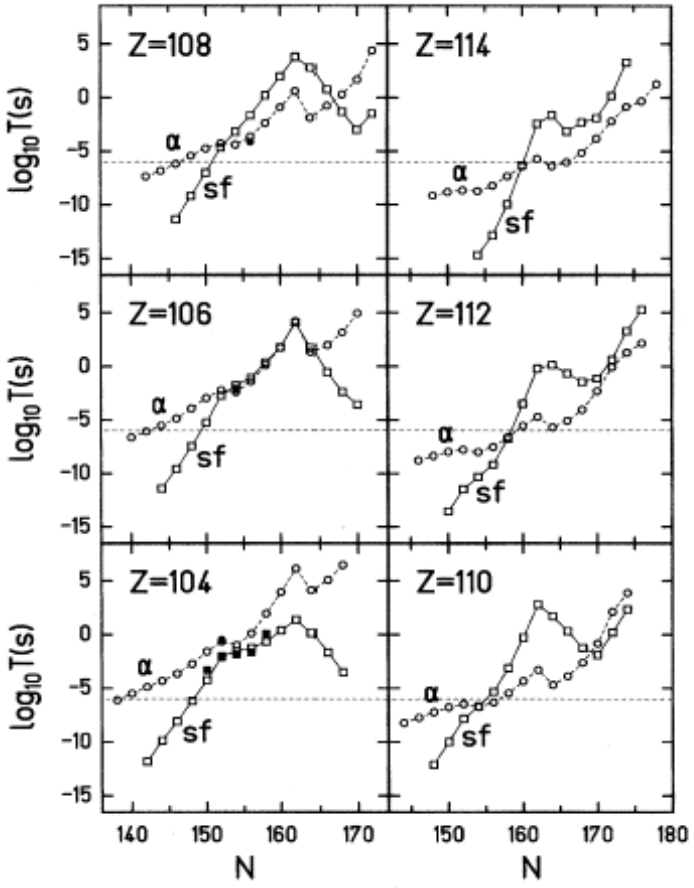
Introduction

Theoretical calculations show that, in the region of the heaviest elements, liquid drop fission barriers tend to decrease to zero. Therefore, the occurrence of nuclear shells is of special importance for the stability of nuclei [1,2]. Experimentally, the influence of deformed sub-shells at Z=108 and N=162 have been confirmed, with the 300-fold increase in half-life of ^{269}Hs$_{161}$ compared to ^{267}Hs$_{159}$ [3] and our recent discovery of ^{270}Hs$_{162}$ with collaborators in Europe [4]. Production of ^{271}Mt$_{162}$ would allow further examination of the N=162 sub-shell. There are many valid reasons to produce ^{271}Mt:

This reaction type (^{238}U + medium mass projectile) provides access to many nuclides near the deformed sub-shells. The 88-inch cyclotron can provide high intensity beams of projectiles with A~40 and we have calculated BGS efficiencies in a range of 30% for this reaction type. This type of reaction may have important implication with respect to the chemical study of nuclides with Z > 108.

The cross section for the production of a compound nucleus is influenced by shell effects. The projectile N=20 shell results in lower E* when fusing at the Coulomb Barrier (^{37}Cl$_{20}$), and the doubly-magic deformed shell of ^{270}Hs helps with the Γ_n/Γ_f exit channel, especially at the point where the fourth neutron is evaporated [5].

Alpha-decay systematics can be estimated by comparison with ^{270}Hs and ^{272}110, indicating a half-life of ^{271}Mt ~2 seconds. Both ^{270}Hs and ^{272}110 are dominated by α-decay even though as even even nuclei they are unhindered, and are predicted to have a half-lives of 5s and 1,400μs, respectively. Comparing the ^{271}Mt alpha-decay energy provides us with quantitative information on the strength of the shells as shown in the figure below [1]. We expect ^{271}Mt to decay primarily by α-decay, which would produce ^{267}Bh and ^{263}Db. Production of these nuclides would provide more information on their (α and sf) branching ratios.



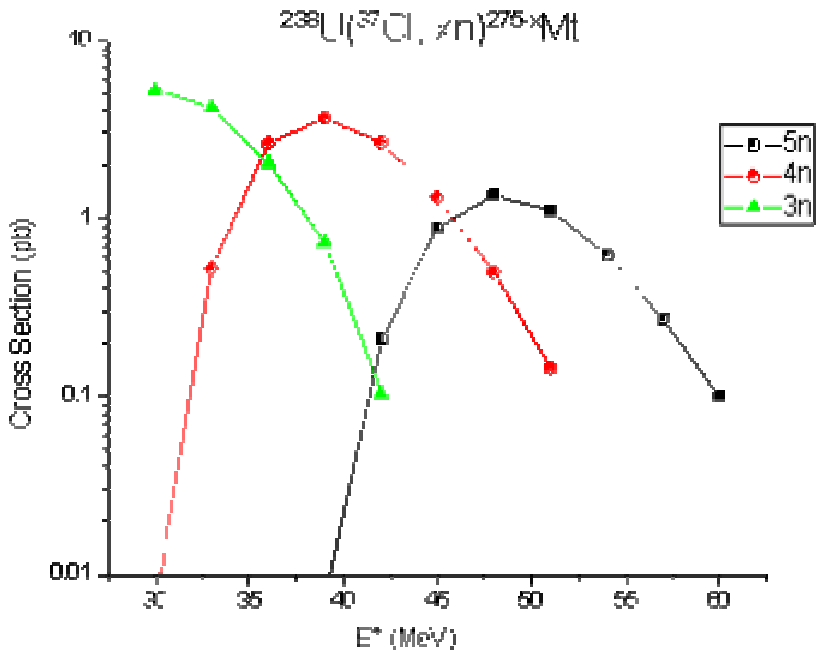
Below are some of ^{271}Mt's predicted alpha decay partial half lives.

Q_α (MeV)	$T_{1/2}$ (s)	Reference
9.91	~10^{-4}	I. Muntian, et al. [6]
10.14	~10^{-6}	G. Royer and R.A. Gherghescu [7]
9.3	26.92	P. Möller, et al. [8]
9.45	1.58	S. Cwiok, et al. [9]

Spontaneous fission may play a significant role in the decay of ^{271}Mt even though odd-A nuclides are hindered with respect to this decay mode as compared to their even even counterparts.

Lastly, discovery of a long-lived (> 1s) isotope of Mt would allow the first-ever chemistry experiment of this element. Presently, the highest Z atom to be studied chemically is Hs, in work that our group collaborated with colleagues in Europe [10], and extension of the Periodic Table to Mt would represent an important advance in basic science.

We expect to produce ^{271}Mt via the ^{238}U(^{37}Cl,4n) reaction. Our motivation for this target-projectile combination comes from recent work at Dubna [11] where they reported a 2.5pb cross section for the reaction ^{238}U(^{34}S,5n) ^{267}Hs, and the identification of three atoms of ^{267}Hs. We have run HIVAP (with the Schädel parameters) for our proposed reaction, shown below:



Lighter Mt isotopes were first synthesized in 1982 by Münzenberg and collaborators [12]. Meitnerium's chemistry has never been studied due to the fact that its two known isotopes (^{266}Mt and ^{268}Mt) have half-lives much less than one second. In order to perform the first-ever chemistry of Mt, one would first need to synthesize a longer-lived isotope. Hulet and collaborators attempted such an experiment [13], but were only able to establish a 1 nb cross section upper limit on the formation of ^{272}Mt.

Experimental

Uranium targets were produced at Oregon State University by evaporating a thin layer of UF_4 upon a 2 μm thick Al foil. Uranium thickness was measured by weighing, and uniformity and thickness were confirmed by counting small sections of a target in an α-chamber. For the third run, average target thickness was 400μgU/cm^2; the two earlier runs were similar.

Reaction products were separated in flight by the Berkeley Gas-filled Separator (BGS) and implanted in the focal plane detector. The focal plane detector consists of a five-sided box of vertical Si strips measuring 18cm x 6cm x 6cm; using this array of strips we can determine the horizontal and vertical position of the event in addition to the energy and elapsed time. The four box sides (referred to collectively as the upstream detectors) are used to record escape α's during our beam shutoff period. In addition, a multi-wire avalanche counter (MWAC) was mounted upstream of the focal plane detector, and a Si detector was mounted downstream of the focal plane as a punch-through detector. Both the MWAC and the punch-through detectors functioned to veto uninteresting events in the focal plane.

We employed an automated beam chopper in this experiment. During the experiment, should a correlated EVR-α event occur with certain time and energy windows, the beam would be deflected away from the target chamber for a set period of time. Should another correlated α be recorded, the beam shutoff would be continued for another set period of time. Deflecting the beam allows the upstream detectors to be utilized without the interference of scattered beam.

Discussion

A complicating factor encountered in carrying out this experiment as well as data analysis is that the evaporation residues lose most of their energy as they transit through the MWAC, resulting in implant energies below 1MeV (signals below 500keV). Indeed, steps were taken to reduce the amount of material encountered by the EVRs, especially in replacing the PPAC with an MWAC. We ran test reactions during this experiment, producing Fr and Es isotopes, to measure their range in the MWAC and confirm published range tables. We have concluded that our ranges were 15% less than published data. We plan to reduce the effective thickness of the MWAC from 3.3μm mylar to 2.4μm mylar in order to increase the EVR implant energy.

The Heavy Element Group at LBNL led an attempt to synthesize ^{271}Mt at the LBNL 88-inch cyclotron. The reaction of 195MeV (center of target) ^{37}Cl + ^{238}U was carried out in a series of three experiments during November 2002 & April/May 2003. Total beam dose delivered during these three experiments was 3.2×10^{18} particles. Data analysis is in progress, though no correlated decays attributable to the Mt-Bh-Db-Lr chain have been seen so far, leading to a single event upper limit cross section of 0.63pb. Future experiments at higher beam energy are planned to further explore the 4n and 5n exit channels with this beam and target combination.

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Random probability analysis of recent ^{48}Ca experiments

J.B. Patin[1], K.J. Moody[1], J.H. Landrum[1], C.A. Laue[1], D.A. Shaughnessy[1], M.A. Stoyer[1], J.F. Wild[1], V.K. Utyonkov[2], Y.T. Oganessian[2]

[1] Lawrence Livermore National Laboratory, Livermore, USA
[2] Joint Institute for Nuclear Research, Dubna, Russia

jbpatin@llnl.gov

A long experimental run was performed at the Dubna U400 Cyclotron Facility bombarding ^{249}Cf with ^{48}Ca aimed at producing isotopes of element 118. Recent independent data analysis of the information gathered during this experiment was performed at LLNL and shall be presented. Two interesting events shall be discussed in detail. The Monte Carlo random probability analysis developed at LLNL for such heavy element experiments was performed for these data and the implications from such analysis will be presented.

Much of the support for the LLNL scientists was provided by the US DOE under Contract W-7405-Eng-48.

Structure effects in photofission

N.N. Son[1], T.D. Thiep[1], P.V. Cuong[1]

[1] Institute of Physics, Vietnam

ngson@fpt.vn

We report on the fission experiments performed with bremsstrahlung beams. The mass distributions for a series of actinide nuclides from Th-232 to U-238 have been measured. The data were analysed in the framework of the statistical model which incorporates total statistical equilibrium between degrees of freedom at scission point and post fission dynamics and both shell effects in the fragments at the scission point and post-scission shell effects. The analysis allowed obtaining the systamatics on shell structure and odd-even effects in photofission of actinides and new understanding structure effects in photofission.